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National Laboratory for Sustainable Energy

Modeling conically scanning lidar error in complex terrain with WAsP Engineering

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Abstract (max. 2000 char.):

Conically scanning lidars assume the flow to be homogeneous in order to deduce the horizontal wind speed. However, in mountainous or complex terrain this assumption is not valid implying an erroneous wind speed. The magnitude of this error is measured by collocating a meteorological mast and a lidar at two Greek sites, one hilly and one mountainous. The maximum error for the sites investigated is of the order of 10%. In order to predict the error for various wind directions the flows at both sites are simulated with the linearized flow model, WAsP Engineering 2.0. The measurement data are compared with the model predictions with good results for the hilly site, but with less success at the mountainous site. This is a deficiency of the flow model, but the methods presented in this paper can be used with any flow model. An abbreviated version of this report has been submitted to Meteorologische Zeitschrift.
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Contents

1 Introduction

Lidars (**li**ght **d**etection **a**nd **r**anging) are becoming an alternative to meteorological masts for vertical profile measurements for the assessment of wind energy potential. They have several advantages over traditional anemometry such as ease of deployment and that large heights can be reached without excessive costs (Emeis, Harris and Banta 2007). They have shown encouraging results reproducing cup anemometer wind speeds within a few percents both on- and off-shore, and several different types of lidars have been investigated thoroughly (Kindler, Oldroyd, Macaskill and Finch 2007, Courtney, Wagner and Lindelöw 2008a).

This success has been limited to flat terrain and it is the purpose of this paper to investigate the performance in mountainous terrain, occasionally called *complex terrain*. Here the the flow is no longer homogenous and that can give a large bias on the horizontal wind speed estimated from the lidar. To illustrate this very simply Figure 1 shows a lidar shooting at an angle φ from vertical upwind and downwind, situated in flow where the horizontal wind speed U is constant, but where the vertical wind speed W changes linearly with the downwind position x. This could crudely mimic the flow over a hill where (in case of $\alpha \equiv dW/dx$ negative) the upstream is tilting upwards and downstream downwards. The projected wind speed on the upwind beam is $v_{up} = -(U + h\alpha)\sin\varphi$ while it is $v_{down} = (U + h\alpha)\sin\varphi$ for the downwind beam. Assuming wrongly horizontal homogeneity, we can calculate the horizontal velocity as estimated from the lidar

$$U_{lidar} = \frac{v_{down} - v_{up}}{2\sin\varphi} = U + h\alpha \tag{1}$$

and we see in the case of negative α that the horizontal wind is *underestimated*.

One remarkable fact seen from (1) is that the underestimation is not diminished as φ tends to zero. In other words, reducing φ will not reduce the bias on the horizontal velocity. It is a simple exercise (see section 2), to show that the same is true for a more realistic setting, where the horizontal wind is obtained from a conical scan in an arbitrary linear flow: $U_i(\boldsymbol{x}) = U_i(\mathbf{0}) + x_j \partial U_i/\partial x_j$.

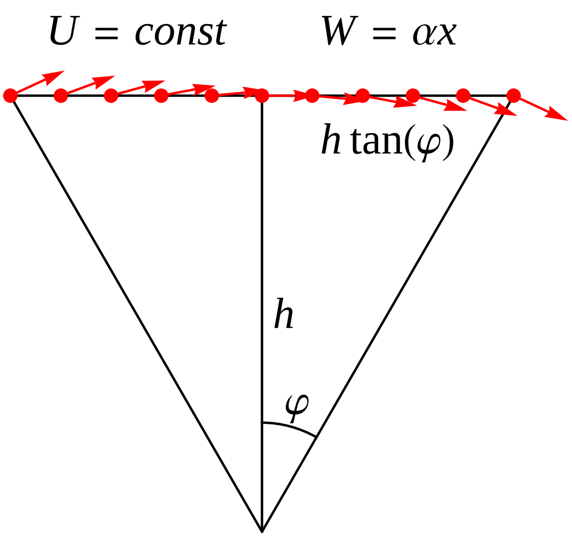

Figure 1. Simplified lidar scanning geometry in a linearly changing mean flow. The lidar is shooting up- and down-stream with a half opening angle φ. The horizontal component of the mean wind U is constant while the vertical component W changes linearly with position x.

We studied the bias caused by inhomogeneous flow, both by comparing collocated mast and lidar measurements in complex terrain, and by predicting the bias by help of a simple flow model. We focus on the continuous wave (cw) lidar ZephIR developed by QinetiQ (Smith, Harris, Coffey, Mikkelsen, Jørgensen, Mann and Danielian 2006), but the basic problem also applies to sodars as well (Bradley 2008).

The ZephIR is used to measure a vertical wind profile with the height ranging from 10 to 150 m. At each altitude it measures the radial velocity in a circular pattern with a cone angle of 30.4° from which the horizontal wind speed can be derived. The crucial assumption in the process of calculating the horizontal wind from the radial measurements is that the flow is homogeneous within the scanned area. Any lack of homogeneity will introduce an error. To model lidar measurements and predict the error for different wind directions for a particular terrain we have analyzed two experimental data sets from two Greek sites: Lavrio and Panachaiko. At Lavrio, Centre for Renewable Energy Sources (CRES) (Foussekis, Mouzakis, Papadopoulos and Vionis 2007) has a test facility and at Panachaiko a wind park. In both sites the lidar is far from any wind turbine and very close to the meteorological reference mast. While the first site is situated in a gently sloping terrain the second site has a very complex structure and flow conditions. At both sites the lidar and meteorological mast data have been collected and flows for the same conditions are simulated with the WAsP Engineering flow software developed by Risø (Mann, Ott, Jørgensen and Frank 2002). Finally, real data are compared with the model results.

2 Simplified analysis

As stated in the introduction we shall now re-derive (1) in a more general way, where the mean wind field can vary linearly in any way and where the wind speed is determined from the lidar by fitting a trigonometric function to the radial velocities. Without loss of validity the analysis is ignoring the fact that the QinetiQ lidar only measures the magnitude of the radial wind speed, not the sign.

Assume the mean wind field $\boldsymbol{U} = (U, V, W)$ to vary linearly

$$U_i(\boldsymbol{x}) = U_i(\boldsymbol{0}) + x_j \frac{\partial U_i}{\partial x_j} \tag{2}$$

over a volume enclosing the lidar scanning circle. The origo of the coordinate system $\boldsymbol{x} = \boldsymbol{0}$ is the center of the scanning circle elevated by h over the instrument. Let

$$\boldsymbol{n} = (\cos\theta \sin\varphi, \sin\theta \sin\varphi, \cos\varphi) \tag{3}$$

denote a unit vector in the direction of the laser beam, where φ is the half opening angle of the cone and θ the azimuthal angle. The radial wind speed v_r measured at an azimuthal angle θ is the projection of $\boldsymbol{U}$ onto $\boldsymbol{n}$:

$$v_r(\theta) = \boldsymbol{n}(\theta) \cdot \boldsymbol{U}\left(\boldsymbol{n}(\theta)l - (0,0,h)\right), \tag{4}$$

where the velocity field is evaluated in the position of the focus of the laser beam. Here $l = h/\cos\varphi$ is the focus distance. The additional variations of the radial velocity due to lack of homogeneity may be expressed as $v_r'(\theta) = v_r(\theta) - \boldsymbol{n}(\theta) \cdot \boldsymbol{U}(\boldsymbol{0})$, and it can be written in terms of the velocity gradient:

$$v_r'(\theta) = n_i(\theta)\left(n_j(\theta)l - \delta_{j3}h\right)\frac{\partial U_i}{\partial x_j}. \tag{5}$$

Substituting (3) into this equation and ordering the terms as a Fourier series in θ we finally get

$$v_r(\theta) \quad = \quad W\cos\varphi + \frac{l}{2}\sin^2\varphi \overbrace{\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y}\right)}^{=-\partial W/\partial z}$$

$$
\begin{aligned}
&+ \quad \left(U \sin\varphi + l \sin\varphi \cos\varphi \frac{\partial W}{\partial x} \right) \cos\theta \\
&+ \quad \left(V \sin\varphi + l \sin\varphi \cos\varphi \frac{\partial W}{\partial y} \right) \sin\theta \\
&+ \quad \frac{l}{2} \sin^2\varphi \left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} \right) \cos 2\theta \\
&+ \quad \frac{l}{2} \sin^2\varphi \left(\frac{\partial U}{\partial y} - \frac{\partial V}{\partial x} \right) \sin 2\theta \quad . \qquad (6)
\end{aligned}
$$

The horizontal and vertical wind speeds are derived from the lidar measurements by fitting a trigonometric series $a + b\cos\theta + c\sin\theta$ to the data. The vertical wind speed is then $a/\cos\varphi$ while the horizontal components are $b/\sin\varphi$ and $c/\sin\varphi$, respectively. In the presence of a linear deviation from homogeneity we thus get for the wind vector estimated from the lidar:

$$U_{\text{lidar}} = U + h\frac{\partial W}{\partial x} \qquad (7)$$

$$V_{\text{lidar}} = V + h\frac{\partial W}{\partial y} \qquad (8)$$

$$W_{\text{lidar}} = W - \frac{l}{2}\tan^2\varphi \frac{\partial W}{\partial z} \quad . \qquad (9)$$

The important lesson to learn from these equations is that the error due to inhomogeneity of the mean flow will vanish for the vertical component as the half opening angle φ goes to zero, but the errors on the horizontal components are independent of φ.

3 The Experiments

The Lavrio site is located 38 km SE of the center of Athens close to the coast of the Aegean Sea. The experiment took place between 2008-Dec-01 and 2008-Jan-15. The highest point is 200 m ASL and main wind direction is 0°. The 100 m triangular lattice reference meteorological mast is equipped with cup anemometers and vanes at five heights (10 m, 32 m, 54 m, 76 m, 100 m). Cups are to the east and vanes are to the west. There are also ultrasonic 3D Gill anemometers at three heights (34 m, 78 m, 98 m) which are not used in this study due to problems with icing but this does not influence the used cup anemometers and vanes. Additionally, the temperature profile is measured using differential thermometers, as well as, the atmospheric pressure and the solar radiation. Dedicated instrumentation is used for signal protection, filtering and conditioning. The sensors are supported on the mast by the aid of telescopic booms of rectangular cross-section, made of high strength aluminum alloy. The boom cross-section is 50 mm×50 mm at base and 30 mm×30 mm at the end where the sensors are supported. All wind sensors (even the top ones) are mounted at a height of 45 cm above the boom and at a distance of 310 cm from the outer mast leg. The lidar is located nearly 12 m north of the mast. The measurement heights are 32 m and 78 m.

The Panahaiko site is located 165 km northwest of Athens, at Vounogiorgis mountain south east of the village Sella, 14 km south of the Patras Sea. The experiment ran from 2007-Sep-19 to 2007-Oct-11. The terrain in the vicinity of the site is very complex. Highest point is 2000 m in the region where the experiment surrounding is between 1700 and 1750 m ASL. The prevailing wind directions are ENE and SW. The triangular lattice reference meteorological mast have six cup anemometers (10 m, 20 m, 30 m, 40 m, 54 m) and two vanes (40 m, 54 m). Additionally, there are also air temperature and relative humidity measurements at 54 m. The boom cross-section is 40 mm×40 mm. All wind sensors are mounted at a height of 75 cm above the boom and at a distance of 225 cm from the outer mast leg. The lidar is located nearly 20 m WSW of the mast. The lidar measurement heights are 30 m and 55 m.

In both experiments lidar data are collected by the standard QinetiQ software and synchronized with mast data by the CRES WindRose software. Instruments are calibrated according to the requirements of IEC61400-12-1:2005/Annex F and MEASNET guidelines at CRES Laboratory for Wind Turbine Testing. All instrument positions in Global and Hellenic Coordinate system are listed in Table 1.

Table 1. Positions of the instruments in both experiments.

		Geographic Coordinates		**Helenic Coordinate System GRS80**	
Experiment	Site	Lat	Lon	x	y
Lavrio	Mast	$37°46'4.02"N$	$24°3'43.94"E$	505347	4179758
	lidar	$37°46'4.44"N$	$24°3'43.92"E$	505335	4179797
Panahaiko	Mast	$38°12'32.57"N$	$21°52'20.35"E$	313567	4230862
	lidar	$38°12'32.30"N$	$21°52'19.62"E$	313549	4230854

4 Theory and Method

4.1 WAsP Engineering

WAsP Engineering is a linearized flow model developed at Risø DTU. We have tested the model with different resolutions and map sizes and have chosen a small enough resolution that the results did not change significantly. The resolution should be so fine that the lidar's scanning circle is well resolved. For those reasons we choose for the Lavrio site a 4 m resolution with a 2.5 km map size and for the Panahaiko site a 10 m with a 5 km map size. In section 4.3 we go into more detail with the requirements for resolution and domain size and show that the results are in fact not very dependent on these parameters.

4.2 Modeling the lidar error

We want to calculate the radial velocity in the direction of the laser beam v_r in the points forming a circle, where the lidar is measuring. Then we use these values to derive horizontal wind speed in the same way as it is done in the QinetiQ ZephIR. We also calculate the horizontal wind speed at the mast position at the relevant heights.

The QinetiQ ZephIR makes scans in different heights with 50 data points on each circle. These data are fitted to a rectified trigonometric function to give the horizontal wind speed, the vertical wind speed and the wind direction. The instrument has a sign ambiguity on the wind vector, but that is resolved by crudely measuring the wind direction at the instrument.

To simulate the flow in the surroundings of the lidar and the meteorological mast we have constructed a piece of software in C# that calls the WAsP Engineering flow calculation libraries. The following step are done:

- The measurement coordinates and measurements heights are set for the mast and the lidar.
- The unit vectors $\boldsymbol{n}$ in a right handed coordinate system with the first axis is pointing towards east, the second axis towards north and the third upwards are calculated for each beam direction on the scanning circle

$$\boldsymbol{n}(\theta) = \{\sin\theta\sin\varphi, \cos\theta\sin\varphi, \cos\varphi\} \tag{10}$$

where φ is the half opening angle of the cone, approximately 30.4° for the ZephIR, and θ is the geographical angle in which the beam is pointing.

- The position of the ith measurement point with a geographical angle θ_i on the circle is given by

$$\boldsymbol{p}_i = h/\cos\varphi \boldsymbol{n}(\theta_i) + \boldsymbol{p}_{lidar} \tag{11}$$

  where h is the measurement height, and $\boldsymbol{p}_{lidar}$ is the position of the lidar. WAsP Engineering uses the AGL (Above Ground Level) values as heights. So, the height for each point put in must be updated according to the difference between the lidar and point position elevations in order to find the height which is at the conical scan level. After that the horizontal wind speed U_h, the wind direction θ_w and the tilt angle ϕ_w can be calculated with WAsP Engineering at these points.

- The wind vectors are projected on to laser beam direction by

$$v_r(\theta) = U_h \boldsymbol{n}(\theta) \cdot \{-\sin\theta_w, -\cos\theta_w, \tan\phi_w\} \tag{12}$$

- In a homogeneous flow v_r versus θ would take the form of a simple trigonometric function. In complex terrain it may be quite different, but it is still fitted to

$$v_r = U_h \sin\varphi \cos(\theta - \theta_w) + w\cos\varphi \tag{13}$$

  giving estimates of U_h, θ_w and the vertical wind speed w. We ignore the absolute value because the sign of the wind vector is known from the model.

- For the mast simulation, horizontal wind speed, wind direction and tilt values are computed for each cup and vane height.

- The final outcome is the ratio between U_h derived from the lidar circle and the horizontal wind speed at the cup position. A value of one would have been obtained over flat, homogeneous terrain.

4.3 Domain size, resolution and specific method

In figure 2 we show how the calculated results for the lidar error depends on the domain size. We have chosen to do the analysis for the Lavrio site and shown are the results for a resolution of 20 m with a scanning height of 32 m. We show both the results obtained by the elaborate method presented in section 4.2 (top) and the simplified analysis discussed in section 2. In the latter we use simple finite differencing to estimate $\partial W/\partial x$ by calculating the vertical velocity on the upstream and downstream side of the scanning circle. This apparently introduces some noise in the results. It is clearly seen that the results are quite insensitive to the domain size. This is probably so because the horizontal derivative of the vertical velocity on which the error mainly depends is not as sensitive to the domain size as for example the horizontal wind. It is also clear that the simplified method differs from the more correct method with a couple of percent.

Figure 3 show the dependence of the result on the resolution in the WAsP Engineering calculations. Again the dependence is rather weak and a resolution as coarse as half the diameter of the scanning circle seems to be enough to gain resolution independence. Both this fact and the domain size insensitivity promise well for the applicability of our method.

5 Results

At Lavrio, most of the winds are northerly which means it is blowing from lidar to the mast. The scatter plots (Figure 4-top) show generally 5% to 7% errors in wind speed

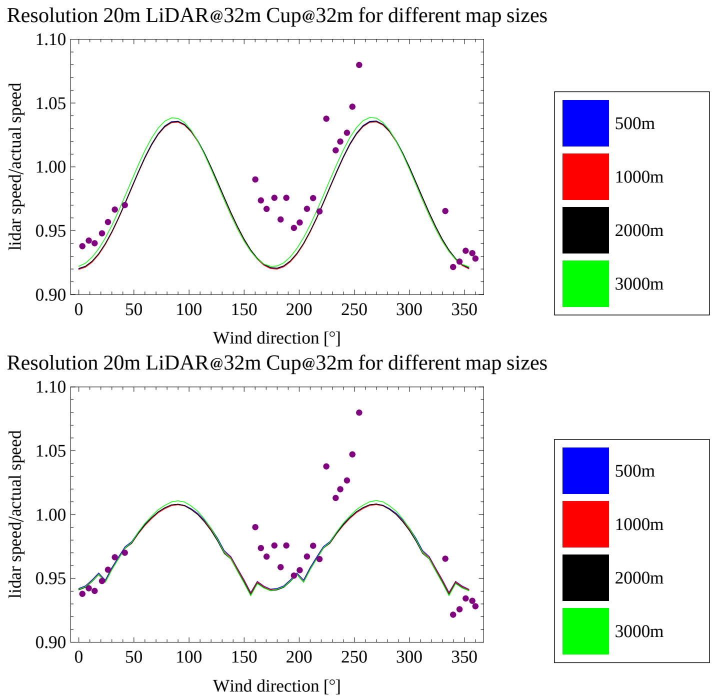

Figure 2. The calculated lidar error depending on domain size. The top shows the results based on the method described in 4.2, while the lower plot is based on the approximate expression (9).

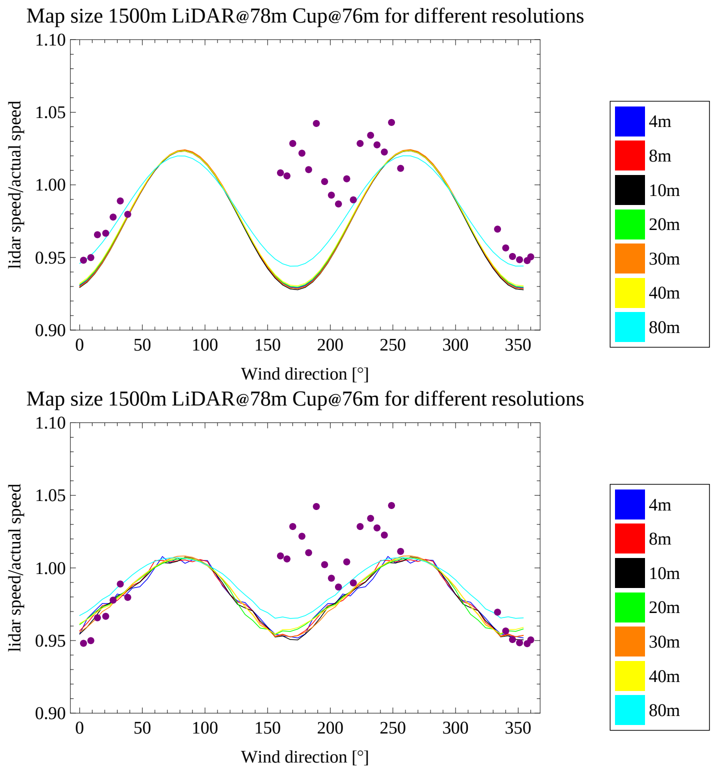

Figure 3. The calculated lidar error depending on resolution. The top shows the results based on the method described in 4.2, while the lower plot is based on the approximate expression (9).

measurements. For the WAsP Engineering model we have used 3 km to 3 km map with 4 m resolution simulating the wind direction from 0° to 360° with 6° bins. We have used all the data from the mast at each height and averaged them according to the wind direction in 10° bins.

The comparison between the model and the measurements is shown in Figure 4 (lower two plots) and shows good correlation in some sectors. The mast is voluminous, thus the selected data must be far from boom direction which is 113°. These sectors are marked with light grey areas in the plots for ±30°. The ideal ratio line of one is also shown and it represents the cases where there is no difference between the lidar and the mast measurements. The black line is the model and the points are the measurement results.

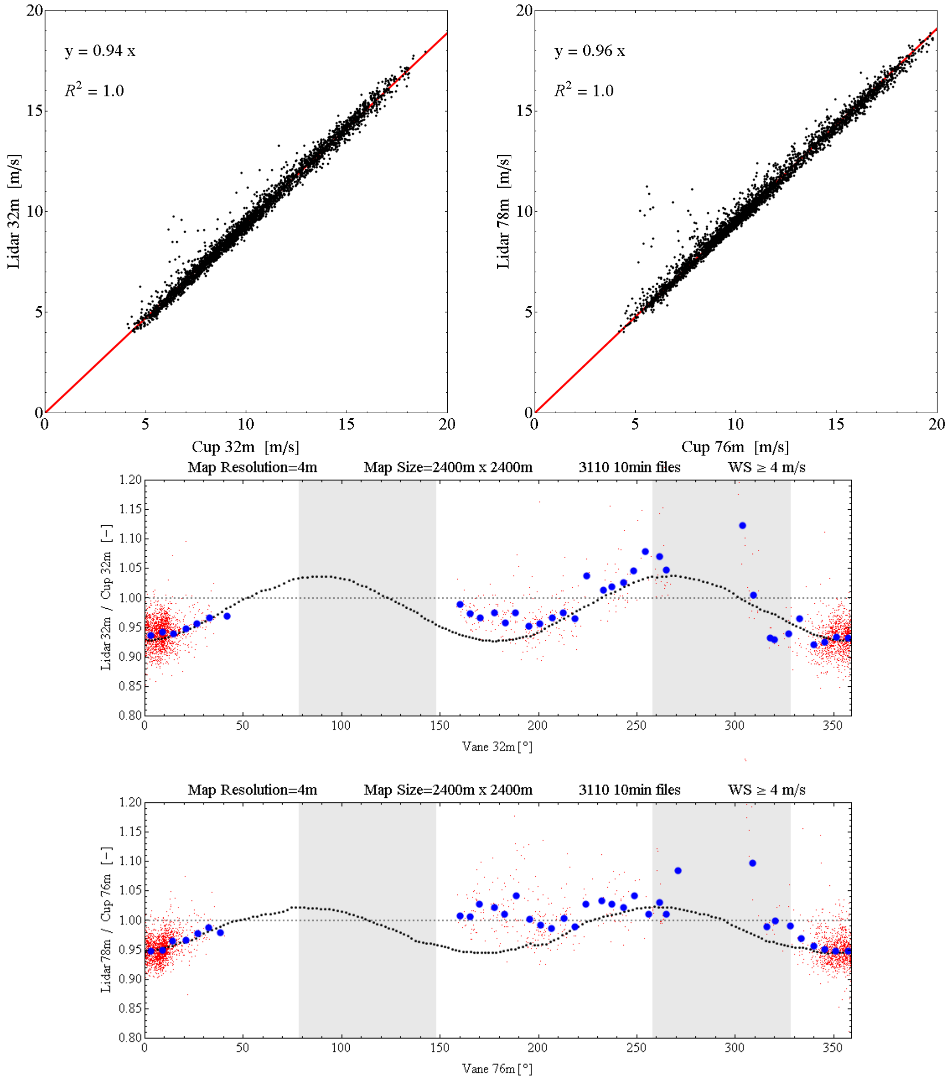

Figure 4. Lavrio: The scatter plots show generally 4% to 6% errors in wind speed measurements (top). Lower two plots are the comparison between the model and the measurement data for two different heights. Small red dots are the error ratio for each 10 minutes measurement, big red dots are the averaged 6° bins according to the wind direction and medium black dots are the model results. The mast shadow is marked with grey rectangles. The ideal ratio line of one, dashed blue, is also shown and it represents the cases where there is no difference between the lidar and the mast measurements. Especially for northerly directions the model predicts the lidar error well for both heights, while for the southerly directions the prediction is not so good.

Especially for northerly directions the model predicts the lidar error well for both heights, while for the southerly directions the prediction is not so good. We believe this can be a result of the limitation of WAsP Engineering. In southerly directions very close to the site there are steep slopes. In this sector and height, the flow model has difficulties predicting the tilt angles as compared to sonic measurements for periods with no icing problems.

The second site, Panahaiko, is much more complex than Lavrio, so there are many sectors which could be problematic for WAsP Engineering to model. The scatter plots in Figure 5 (top) show data for all directions. The mast at Panahaiko is smaller than at Lavrio so the sector with flow distortion is smaller ($\pm 25°$) shown in grey in the figure. The boom direction is $210°$.

The comparison between the modeled error and the measurements as a function of direction is shown in Figure 5 (lower two plots). It is not a perfect prediction, but the model gives the right order of magnitude for this complex site.

The outliers mainly seen for the larger heights in figure 4 and 5 are probably due to cloud return as discussed in Courtney, Wagner and Lindelöw (2008b).

5.1 Ruggedness index (RIX)

The ruggedness index (RIX) of a given site is defined as the fractional extent of the surrounding terrain which is steeper than a certain critical slope (Bowen and Mortensen 2004, Mortensen, Bowen and Antoniou 2006). The index was proposed as a coarse measure of the extent of flow separation and, thereby, the applicability of WAsP, since it assumes that the surrounding terrain is sufficiently smooth to ensure mostly attached flows. The operational envelope of WAsP is, strictly speaking, a RIX value of $\sim 0\%$. This requirement also applies for WAsP Engineering since it is the same type of linearised flow model. The RIX concept has been used extensively over the last 10 years in wind resource assessment and sitting studies in complex terrain.

The RIX value for one site is calculated for a number of radii originating at the site, by dividing each line into segments defined by the crossing of the line with the height contours. The sum of the line segments representing slopes greater than a critical slope (0.3 for our study as it is used in WAsP) divided by the total sum of the segments is then the RIX value of the radius in question (Bowen and Mortensen 2004). The overall RIX value for the site, the site ruggedness index, is then simply the mean of the sector-wise RIX values.

Figure 6 shows a graphical representation of the ruggedness index for the two experimental sites. The center points are the lidar positions. Site ruggedness index for Lavrio and Panahaiko are 10% and 30% respectively. At both sites high RIX values seem to be correlated with the sectors where the model has problems predicting the error.

6 Conclusion

Lidars, used over flat homogeneous terrain, show errors in the mean wind speed of only a few percent. We have shown that in complex terrain of the type commonly used for wind turbine parks, errors in the horizontal wind speed as measured by a conically scanning lidar can be of the order of 10%. This is due to the lack of horizontal homogeneity of the flow, which is assumed in the interpretation of the lidar data. The findings are based on two experiments involving collocated lidars and meteorological masts in complex terrain, together with flow calculations over the same terrains. For that calculation we use WAsP Engineering, and we find that the calculations match the experiment except for some sectors where the terrain is particularly steep. This is not surprising, since the WAsP Engineering is built on a linearized flow model, which is only valid for limited terrain

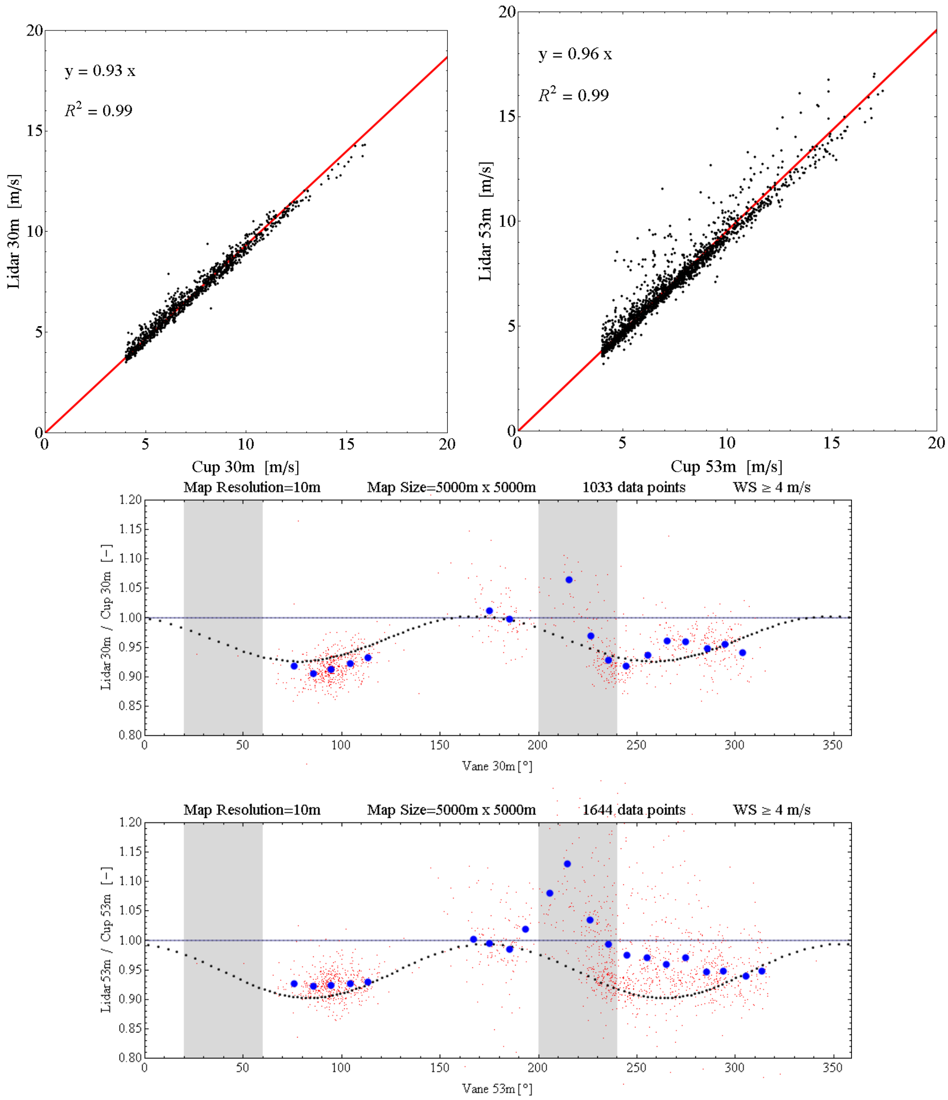

Figure 5. Panahaiko: The scatter plots show generally 4% *to* 7% *errors in wind speed measurements (top). Lower two plots are the comparison between the model and the measurement data for two different heights. Small red dots are the error ratio for each 10 minutes measurement, big red dots are the averaged* 10° *bins according to the wind direction and medium black dots are the model results. The mast shadow is marked with grey rectangles. The ideal ratio line of one, dashed blue, is also shown and it represents the cases where there is no difference between the lidar and the mast measurements. It is not a perfect prediction, but the model gives the right order of magnitude for this complex site.*

slopes. To make more reliable predictions of the error in very steep terrain, other more advances flow models must be used. We investigate the resolution needed for the WAsp Engineering calculations.

We envisage two solutions on how lidars can be used to estimate wind resources in complex terrain. The first is to use a conically scanning lidar, but instead of using the horizontal winds prone to errors, one could use the radial speeds directly to assimilate into a flow model. The second is to use several lidars focused roughly at the same point, so the assumption of homogeneity of the flow is superfluous. This last concept is suggested by Mikkelsen, Mann, Courtney and Sjöholm (2008).

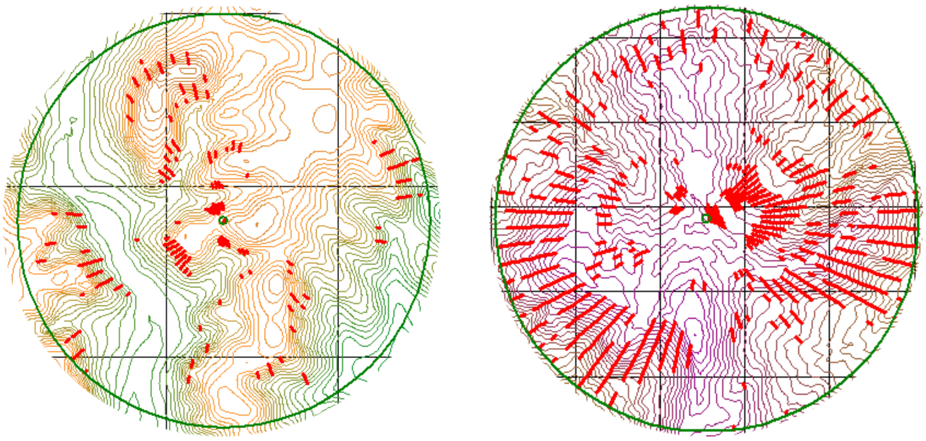

Figure 6. RIX plots for both sites; Lavrio (left), Panahaiko (right). Middle point is where the lidar is. RIX values (red) are calculated for the map size (each square is 1*x*1 *km) and 0.3 RIX threshold with WAsP Tools. The sector where the model has problem have high RIX values. The site RIX value for Lavrio and Panahaiko are 10% and 30% respectively which is outside the operation envelope of WAsP Engineering.*

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